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F03B 13/14

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US 5074710 A **US 5027000 A** **US 4466244 A**
US 4441316 A

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(54) Abstract Title
Wave energy device

(57) A wave energy device comprises at least one open-ended tube 1,9,10,11 for insertion into a body of water and a power conversion and pressure control module 4, which may include a pneumatic turbine, blower, exhauster or latching valves for adjusting the pressure of a fluid in the tube, such as air (3, Fig 1) or a liquid less dense than water (18, Fig 8), and thus adjust the mean water level within the tube 1,9,10,11. Power from the flow of fluid 3 caused by waves passing the device may be harnessed by a power converter, such as a cross-flow radial turbine (25, Figs 5c-e). The tubes 1,9,10,11 may be of different lengths (Fig 5) or be telescopically adjustable (6, Fig 3) and may be straight or helical.

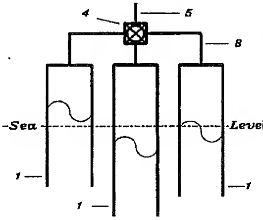

Fig.5

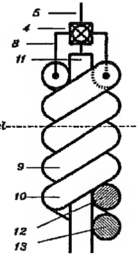

Fig.6

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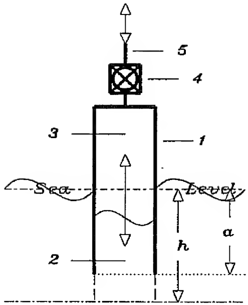

Fig.1

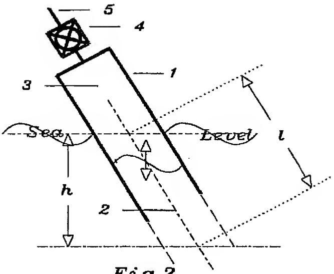

Fig.2

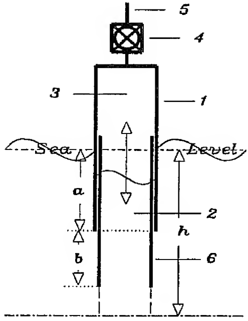

Fig.3

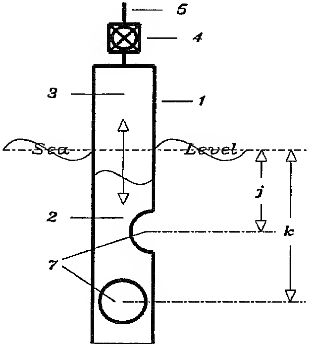

Fig.4

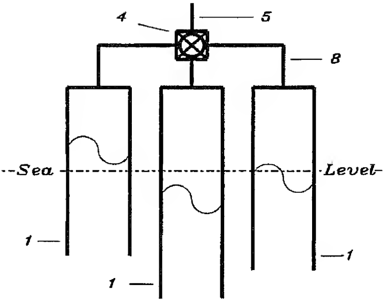

Fig.5

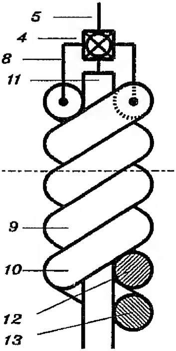

Fig.6

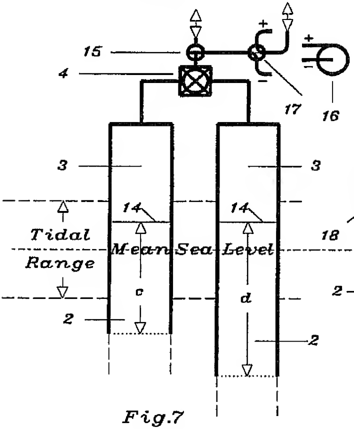

Fig.7

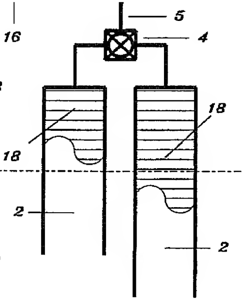

Fig.8

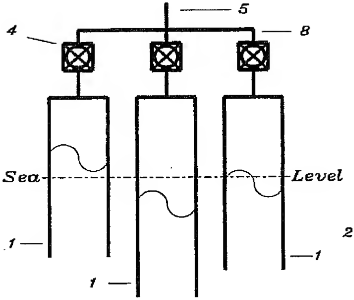

Fig.5a

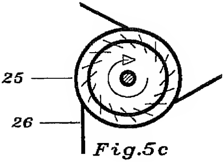

Fig.5c

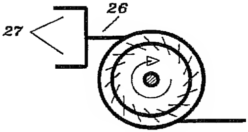

Fig.5d

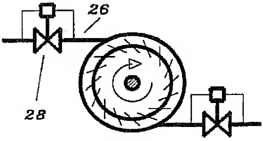

Fig.5e

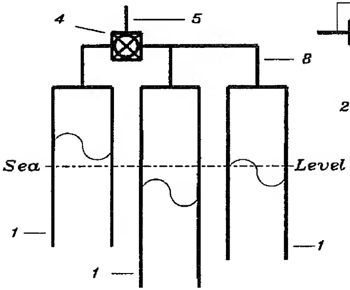

Fig.5b

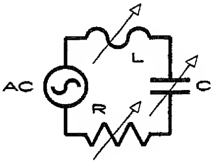

Fig.5f

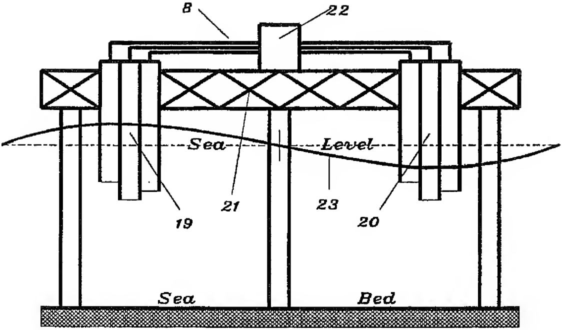

Fig.9

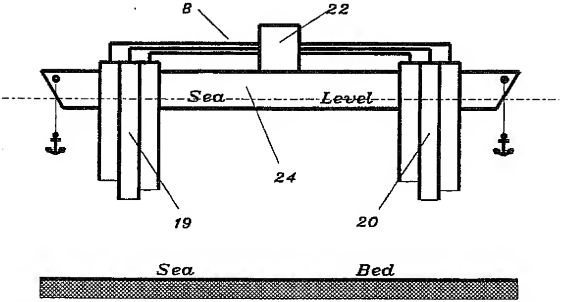

Fig.10

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Wave Energy Devices

This invention concerns devices for abstracting power from the energy in natural water waves encountered, for example, in oceans, seas, lakes, estuaries and the like.

It is known that if one end of a straight tube is suspended in the sea while the other end remains above the surface of the water, sympathetic oscillation of the water and air in the tube occurs in response to the driving force of the surrounding waves. A similar phenomenon can also occur in natural gullies and caves around the coastline.

When the frequency of the waves inducing movement of fluid in the tube is in harmony with the natural period of oscillation of the fluid in the tube, a resonance can be set up whereby fluid movement within the tube becomes intensified. Such a device is generally called an oscillating water column ("OWC"), even though in this case both air and water necessarily oscillate.

This principle has long been used at low efficiencies, for example, to blow foghorns or charge batteries on navigational buoys. More recently, this principle has been the basis of several attempts to extract significantly larger-scale power from waves at higher efficiencies, for example for use as mains electricity ashore. However, one disadvantage of using a single OWC as an energy collector is that its efficiency of wave energy collection over the period of a year is limited by the narrow range of its frequency response. This means that installation sites have to be found where the wave regime is predictably constant throughout the year to suit the characteristics of the particular wave energy device.

PCT/GB95/00793 describes floating wave energy devices using single or multiple OWC's with at least one tube which in use extends below the effective wave base. In a preferred embodiment a cup member is positioned over the top of a bundle of OWC tubes, the lower periphery of the cup extending below the wave surface, thereby enabling the frequency range of the device to be broadened as a result of the varying pressure of the air in the cup being shared between the various tubes.

According to the present invention there is provided a wave energy device comprising at least one open ended tube for insertion into a body of water from which such energy is to be abstracted when one end of the tube is located below the surface of the water throughout the passage of waves past the device, means for harnessing power from the resulting changing water level in the tube as waves pass the device, and pressure adjustment means for controlling the pressure of the fluid within the tube above and below atmospheric pressure thereby to adjust the mean water level within the tube.

The pressure adjustment means preferably comprises a blower/exhauster or other means such as latching valves which can increase or reduce the pressure on the fluid in the tube above the water therein.

It is particularly preferred to include a plurality of said tubes which are of different lengths from each other. The tube or tubes can be substantially straight or they can have other shapes, for example substantially helical. They can also be of different and/or variable cross-section along their respective lengths.

The fluid in one of said tubes is preferably in communication, either directly or via the means for harnessing the power, with the fluid in at least one other of said tubes, thereby enabling different effective resonant lengths of fluid containing tube to be achieved. The pressure adjustment means can then control the mean common pressure of the fluid in the communicating tubes.

As an alternative to or in addition to using a plurality of individual tubes of different fixed lengths, the lengths of the tubes themselves can be made to be adjustable, for example by apertures along their length or by slider arrangements.

One preferred form of device in accordance with the present invention includes at least two of said tubes positioned to respond at any one time to different phase angles of the wave motion.

Devices in accordance with the present invention can be made floatable in their own right, but if desired they can include mount means for mounting them on floating or static objects, for example buoys, gas and oil rigs, pontoons, and piers. It can also be advantageous for the mount means to enable the inclination of the longitudinal axis of the tube to be varied.

Although the fluid above the water in the tube or tubes will usually be air, it can be desirable to use a water-immiscible liquid, for example oil or even a gas other than air.

As will also be appreciated, devices in accordance with the present invention can include mechanical, hydraulic, pneumatic, electric, electronic or other sensor-operated anticipatory

control systems for controlling the mean system pressure adjustment means. This can enable the pressure in the tube or tubes to be adjusted to improve the efficiency of the devices in abstracting energy from the waves.

Using single or multi-phase oscillating fluid columns, each of which having its own discrete, fixed or tuneable resonant frequency and operating alone or in combination with other columns, can provide an aggregate fluid movement and pressure cycles within the overall system which can, for example, be used to drive hydraulic or pneumatic turbines for conversion into mechanical, electrical or other forms of useable power. Possible applications of the technology include, but are not limited to, supplying mainland electricity grids, stand-alone power supplies for remote communities such as small islands, services on offshore marine installations such as oil and gas rigs, or lighting and telemetry on navigational buoys.

Devices in accordance with the present invention can be mounted on floating structures or structures which are rigidly fixed to the seabed or shore. In general there is no minimum limit to the length of the longest pipe or hollow section employed, nor is there in general a need for an inverted cup member. However, the present invention enables the natural resonant frequencies for the OWC's employed to be designed and adapted according to circumstances.

A major factor in determining the natural resonant frequency of oscillation of fluid columns in OWC pipes is the "effective" length of the water and/or other fluids therein, this being the length of water and/or other fluids in the pipe under zero wave conditions plus an allowance based on the notional amplitude excursion of water beyond the immersed and open seaward end of the pipe. This critical length can be determined and fixed by design or it can be actively controlled, for example by extensible pipes, by organ-stop type openings in the body of the pipe, or by other means.

Other factors affecting the nature of the resonant response are fluid resistance, flows and differential pressures within the system, and the orientation of the pipe axes with respect to the vertical. The latter can be fixed and determined by design and/or adjusted to suit the incident wave regime in a time-averaged or real time mode, using appropriate sensors, valves and actuators.

When turbines are used as the means for harnessing the power, they can be operated by a liquid and/or a gas within the system, and they can be of the unidirectional self-rectifying type in which they have a constant rotational direction irrespective of the direction of actuating fluid flow, several different types being available, an example being known as the "Wells" unit. Alternatively, more conventional turbines, or perhaps reciprocating pistons or diaphragms, can be used for which external flow-rectification would usually be required, for example using flap-valves or otherwise for rectification.

The individual OWC pipes can be other than straight and of fixed circular cross-section, for example they can be in the form of toroidal helices.

Embodiments of device in accordance with the present invention will now be described by way of example only.

Figure 1 shows a single vertical OWC with power converter and pressure controls;

Figure 2 shows the single OWC of Figure 1 but inclined to the vertical;

Figure 3 shows a further single OWC but with an adjustable length tube;

Figure 4 shows a still further single OWC but with openings along its length;

Figure 5 shows a combination of three single OWC's each of different lengths from the others;

Figure 5a shows a variant of the device of Figure 5;

Figure 5b shown a further variant of the device of Figure 5;

Figures 5c and 5d show turbine arrangements for the devices of Figure 5 and 5b respectively;

Figure 5e shows a turbine with flow control valves;

Figure 5f represents an approximate electrical analogy of a single column device in accordance with the present invention;

Figure 6 shows an embodiment having helical OWC tubes;

Figure 7 shows an embodiment including a pair of OWC's and pressure control of column length;

Figure 8 shows an embodiment including a pair of OWC's operating with a fluid combination other than air and water;

Figure 9 shows an embodiment including multiple OWC's affixed to a seabed-mounted gantry; and

Figure 10 shows a still further embodiment including multiple OWC's and affixed to a floating vessel.

It is an essence of the present invention that any practical device to be built from it shall embody the underlying principle of broad-band wave energy collection. According to the invention, this can be provided by single OWC's whose frequency determining parameters are capable of live adjustment and tuning to suit the incident wave and tidal regime of the moment or by a multiplicity of OWC's each having fixed but differing frequencies which act in concert or by a combination of both

these expedients. The following descriptions and illustrations are to be read in this context.

Figure 1 is a schematic representation of a tube 1 of uniform cross-section with one end substantially closed which is vertically mounted, by means not shown, in a body of water so that its lower, open end remains below the surface of the waves. Sympathetic oscillations of a water column 2 and an air column 3 within the tube 1 can be induced by the driving force of the incident waves. Air 3 in the tube 1 is cyclically inspired or expelled through a power conversion and pressure control module 4 which might, for example, include a pneumatic turbine and fluid resistance/differential pressure adjustment valve which together modulate the internal air flow rate, and hence influence the natural period of oscillation in the column, as principally determined by the "effective" length "h" of the water column 2. This "effective" length is, for the reason given earlier, greater than the still-water immersion depth "a" as shown.

The power conversion and pressure control module 4 in turn connects through a pipe 5 either directly to atmosphere or to a closed plenum of some sort (not shown) or to other OWC units, as will be described below. It should be noted that the frequency-determinant lengths may also obviously be adjusted by moving the OWC tube up or down with respect to its mounting.

Figure 2 shows another method by which the natural resonant frequency of the OWC may be altered. If the axis of the tube 1 is inclined to the vertical, for example using live means (not shown), then the new "effective" column length "l" increases trigonometrically beyond the vertical height "h", according to the angle of inclination, to provide a longer period oscillation.

A further method of adjusting the column length and frequency is illustrated in Figure 3, the basic tube 1 having a telescopically extensible member 6 which enables the original

effective column length "h" to be varied by increasing the still water immersion depth from "a" to "a+b", this being effected by means not shown.

Figure 4 illustrates the possibility of varying the still-water immersion depth using openings 7 in the immersed tube 1 at various depths "j" and "k", these being openable and closable by means not shown.

Figure 5 shows a number of individual OWC's interlinked through pipes 8 to a single power conversion and pressure control module 4. The natural periodic frequencies to which the resulting overall device responds becomes more than the sum of the parts because the columns not only interact individually with incident waves but also with each other. Dynamic analysis of a multiple unit device is complex and involves the method of mounting of the device. However, as will be appreciated by those skilled in the art, the columns in any two units can respond either at their own discrete frequencies or in combination as a composite single column of lower frequency (rather like a U-tube) or that they may produce harmonics and beat frequency modes. Increasing the number of individual OWC's in the combination therefore increases the number of possible permutations and combinations of resonance between the columns and hence the response bandwidth of the device as a whole.

Figure 5a shows a similar arrangement of three OWC's, but in this case each OWC has its own power convertor/pressure control unit each of which being fluidically linked on the opposite side from the OWC's by pipes 8. The the individual power convertors may, if desired, be mechanically joined to a common shaft (not shown).

Figure 5b illustrates another arrangement including three OWC's in which one OWC feeds directly to a power convertor/pressure control unit 4 whilst the outputs from the other two OWC's are combined in a pipe 8 before being passed to the unit 4. This ability to isolate and/or group OWC's can be used with many

embodiments of the present invention having more than two OWC's. It is also possible, using directional control valves (not shown), to vary the combinations and permutations of OWC groupings and thus enable the bandwidth response of the whole device to be adjusted in response to changing sea states.

The device illustrated in Figure 5 has three OWC outputs feeding into a single power/control unit 4. Figure 5c shows schematically how mechanical power can be obtained from multiple separate jet feeds 26 using a single convertor in the form of a crossflow radial turbine 25 as might be applicable for an arrangement similar to that of Figure 5. In any closed system of OWC's, at any particular instant there will usually be some fluid columns that are rising and some that are falling. The direction of flow of fluid through the jets feeds 26 can therefore oscillate in a compensatory way between blowing and sucking. The turbine example here may possibly be fitted with a further inlet/outlet pipe (not shown) giving axial access to the space within the turbine runner and leading possibly to a plenum and/or system gauge pressure control valve.

Figure 5d shows a turbine similar to that of Figure 5c but with the OWC outputs feeding the tubes 27 being grouped together before being passing through the jets 26 as might be applicable for an arrangement similar to that of Figure 5b.

It is particularly preferred that the respective response frequencies of the fluid columns be controlled at or around their respective natural resonant frequencies. One means of influencing the frequency response characteristics of the devices is to modulate the internal system pressures and fluid flow rates.

Figure 5e shows the inputs/outputs to a turbine which is regulated by differential pressure operated proportional flow control valves 28 fitted into feed pipes 26. As will be appreciated, the associated sensors and valves can, if desired, be monitored and actuated by a remote central computer.

By way of general explanation only, Figure 5f illustrates an electrical analogy of the overall principle of the present invention and it shows a simple electrical tank circuit as representing a single fluid column consisting of a resistance R, a capacitance C and an inductance L (which are here shown in series) and driven by an alternating current. This circuit has a resonant frequency "f" where $f = 1/2\pi(LC)^{1/2}$.

When the frequency of the applied alternating current achieves resonance in the circuit, the net reactance of the circuit becomes zero and the total impedance resolves to that of a pure resistance. This resistance is then the only factor limiting the flow of current resulting from the applied voltage. It is clearly possible to tune this tank circuit or otherwise influence its behaviour by varying all or any of the components, and they are therefore shown as variable.

In a similar but not identical way, adjustment of the OWC column lengths and/or the internal system pressures and flow rates therein can alter the resonant frequencies and behaviour of individual OWC's, and thereby the resonant frequency of the device as a whole. As with the electrical analogy, all of these OWC and system parameters can be controlled, and for wave energy devices working in time-averaged or real time mode this can be effected using appropriate algorithms in reaction to the behaviour characteristics of the incident waves.

Figure 6 illustrates the use of individual OWC's which are other than straight tubes, two helical tubes 9 and 10 being wound round a third, straight tube 11 which could, for example, be the leg of a pier or an oil rig but which here is depicted as an OWC with open lower end. The open, seaward ends 12 and 13 of the helical tubes 9 and 10 may be at different depths. The use of toroidal helices enables different ratios of column length to immersed depth to be achieved, for example to suit the installation site.

If devices are mounted in tidal waters and are rigidly connected to the seabed or shore, as shown in Figure 7, variations in the head of water between the desired internal water level 14 and the fluctuating mean wave surface level as a result of tidal variations will need to be adjusted in order to maintain the desired still-water column lengths "c" and "d", and hence frequency responses. An atmospheric vent valve 15, together with a blower/exhauster 16 operating through a directional valve 17 can be used to enable the internal pressure within the system to be increased or decreased as required.

If the internal still-water levels are too high and the current tide level is below them, the vent valve 15 can be employed to dump excess water from the tubes. However, if the still-water levels are too high but the external tide level is higher, the system can be pressurised through a directional valve 17 using the blower/exhauster 16 in blower mode. If the internal still-water levels are too low, the reverse technique can be used either using the vent valve 15 or the blower/exhauster 16 in exhauster mode, depending on relative tidal levels.

Apart from adjustments to compensate for tidal variations, this method of controlling the lengths of the columns of water within the OWC's by adjusting the mean internal system pressure can also be used to vary the frequency response of the system. For example, the desired water column lengths can necessitate the internal still-water level 14 being higher than the external water level, thus implying that the pressure within the system is sub-atmospheric. Alternatively, if the desired still-water lengths are to be below the external water level, an internal system pressure above atmospheric pressure is implied.

Systems in accordance with the present invention can use fluid columns other than air/water combinations. Figure 8 shows the use of a liquid 18 which is less dense than seawater, for example oil, floating on top of the water column 2, and replaces the air of earlier embodiments. Whereas there may or may not still be air or another gas in the plenum to which pipe 5 can

lead, it acting when present as a pneumatic spring or accumulator, this embodiment allows the power converter in module 4 to be fully flooded by the liquid 18 so that it works hydraulically rather than pneumatically. A similar effect could be achieved by raising the water column 2 itself above the level of the power converter module 4 using a partial vacuum.

It is foreseen that a major potential application for this invention will be for the generation of substantial amounts of environmentally benign electrical power. Figure 9 schematically represents an array of devices 19 and 20 fixed to a large and rigid seabed-mounted gantry 21. Fluid power output from the individual OWC's is fed along pipes 8 to a central power conversion and control module 22, where some or all of the inputs may be combined before passing through a single turbine or alternatively, they may be fed separately to a multijet turbine or turbines or other types of power conversion machinery. As shown, each bundle of close-coupled OWC units 19 and 20 is exposed to a narrow phase angle of a sea wave 23 (here shown as monochromatic). However, as a result of the clear spatial separation of the two arrays, array 19 experiences a wave crest while array 20 is in a trough. This can promote an even greater enhancement of the range of response frequencies of the whole system, and it obviously leads to the possibility of controlling the frequency response of the system by live alteration to the spatial separation of the arrays 19 and 20.

Figure 10 shows an embodiment similar to that of Figure 9 but with the arrays 19 and 20 mounted on a floating pontoon 24 having periods of yaw, pitch and roll which are long in comparison with the wave length of the incident waves, thereby presenting a quasi-static mounting. The pontoon 24 can either be anchored on station or moved from place to place to meet temporary power requirements.

Claims

1. A wave energy device comprising at least one open ended tube for insertion into a body of water from which such energy is to be abstracted when the open end of the tube is located below the surface of the water throughout the passage of waves past the device, means for harnessing power from the flow of a fluid within the device resulting from changes in water level within the tube as said waves pass the device, and pressure adjustment means for controlling the mean pressure of the fluid within the device thereby to adjust the mean water level within the tube.

2. A device according to claim 1, wherein the pressure adjustment means comprises a blower/exhauster which can increase or reduce the pressure of the fluid in the tube above the water therein.

3. A device according to claim 1, wherein the pressure adjustment means comprises latching valves.

4 A device according to any of the preceding claims, including a plurality of said tubes which are of different lengths from each other.

5. A device according to any of the preceding claims, wherein the tube or tubes are substantially straight.

6. A device according to any of claims 1 to 4, wherein the tube or tubes are substantially helical.

7. A device according to any of the preceding claims, wherein the tube or tubes are of different cross section along their respective lengths.

8. A device according to claim 4, wherein the fluid in one of said tubes is in communication with fluid in at least one other

of said tubes either directly or via the means for harnessing the power therefrom.

9. A device according to claim 8, wherein the pressure adjustment means can control the mean common pressure of the fluid in the communicating tubes.

10. A device according to any of the preceding claims, wherein the resonant length of the tube or tubes is adjustable.

11. A device according to any of the preceding claims, including at least two of said tubes positioned to respond at any one time to different phase angles of the wave motion.

12. A device according to any of the preceding claims, including mount means for mounting it on a floating or static object.

13. A device according to claim 12, wherein the mount means enables the height and/or the angle of inclination of the longitudinal axis of the tube or tubes to be varied.

14. A device according to any of the preceding claims, wherein the said fluid comprises a water-immiscible liquid or gas other than air.

15. A device according to any of the preceding claims, having at least three tubes and the fluid outputs of two or more thereof being combined before being passed to the means for harnessing power.

16. A device according to any of the preceding claims, including mechanical, hydraulic, pneumatic, electric, electronic or other sensor-operated anticipatory control systems for controlling the pressure and/or fluid flow adjustment means.

17. A wave energy device substantially as herein described with reference to the accompanying drawings.

The Patent Office

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Application No:	GB 9711505.9	**Examiner:**	Robert Crowshaw
Claims searched:	1 to 17	**Date of search:**	4 September 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): F1S

Int Cl (Ed.6): E02B 9/08; F03B 13/10, 13/12, 13/14, 13/16, 13/18, 13/20, 13/22, 13/24

Other: Online database: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	US 5074710	(NORTHEASTERN UNIVERSITY) Note the use of pressure control between two chambers in tidal applications.	
X	US 5027000	(TAKENAKA) Note the use of air pressure control for the wave energy devices.	1 at least
X	US 4466244	(WU) Whole document relevant, but note the different water levels between each of the open ended tubes in the figures.	1 at least
X	US 4441316	(SEC. OF STATE FOR ENERGY) Note the valve 111 which controls the water level in the liquid column in figure 8.	1 at least

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		